THE ^{26}Al - ^{26}Mg RECORD OF CHONDRULES: CLUES TO NEBULAR CHRONOLOGY; Ian D. Hutcheon[1] and Rhian H. Jones[2], [1]Isotope Sciences Division, Lawrence Livermore National Laboratory, Livermore, CA 94551; [2]Institute of Meteoritics, University of New Mexico, Albuquerque, NM 87131

One key to the development of a more quantitative picture of solar system origin is an improved determination of the duration of the solar nebula and of the chronology of events during this earliest epoch of solar system history. For the past several years we have pursued an experimental approach to nebular chronology using the ^{26}Al - ^{26}Mg system ($\tau_{1/2}$ ~ 0.7 Ma) in chondrules and refractory inclusions (CAI) in chondritic meteorites [1]. This study has revealed a striking contrast in the ^{26}Al - ^{26}Mg record between CAI, plagioclase-olivine inclusions (POI) and ferromagnesian chondrules. Evidence of ^{26}Al is widespread in CAI, infrequent in POI and very rare elsewhere. The majority of CAI (excluding hibonite-rich CAI in CM2 chondrites) is characterized by a narrow range of ^{26}Mg*/^{27}Al ratios and can be inferred to have formed nearly contemporaneously (Δt < 0.1 Ma) [2]. In contrast, the few observations of ^{26}Mg* outside CAI yield initial ^{26}Al/^{27}Al ratios much lower than the canonical, early system value of ~ 5 x 10^{-5} inferred from studies of CAI [3-6]. Under the assumption of an initially uniform ^{26}Al distribution, the paucity of ^{26}Mg* in POI and chondrules is most plausibly attributed to late formation, several Ma after CAI [1]. Implicit in this scenario is the assumption that the ^{26}Al - ^{26}Mg chondrule ages, determined from Mg isotope analyses of plagioclase, refer to the chondrule-forming events and not to subsequent parent body metamorphism. An alternative interpretation denies the relevance of ^{26}Al chondrule ages to nebular chronology by asserting that plagioclase in these objects is not a primary, igneous phase but was produced by metamorphic processes such as devitrification of chondrule glass or recrystallization of microcrystalline groundmass precursor material [7]. We have attempted to address these issues by focusing on two of the least metamorphosed meteorites in which parent body effects should be minimized, Kainsaz (CO3.1) and Manych (LL3.1), and by identifying plagioclase-bearing chondrules in which the textural evidence for igneous plagioclase is very strong. We report here the results of our most recent petrographic and Mg isotope study of four plagioclase-bearing chondrules. The absence of ^{26}Mg* in these samples strengthens the argument for late formation of chondrules [1] and suggests that the duration of the solar nebula was comparable to the survival times of circumstellar disks surrounding solar-type, pre-main-sequence stars [8].

Kainsaz KB1 and KB2 are members of the family of reduced, plagioclase-rich porphyritic objects related to Al-rich chondrules [9]. KB1 is a circular, 350 μm diameter chondrule with a primary phenocryst assemblage of plagioclase laths (~An 80) and pyroxene intergrown in an ophitic texture. Low-FeO orthopyroxene cores are overgrown with augite and plagioclase shows minor alteration to nepheline. The groundmass of KB1 is a fine-grained feldspar-silica assemblage; silica is partially altered to ferrosalite. KB2 is a ~1mm long, ovoid inclusion containing three distinct mineral assemblages. 1) A pyroxene-plagioclase-silica assemblage, similar to KB1, consists of low-FeO pyroxene phenocrysts and plagioclase laths in an ophitic texture. Plagioclase is partially altered to nepheline, while the groundmass resembles KB1. 2) A pyroxene-olivine-metal-sulfide region has large grains of clinoenstatite enclosing numerous small, zoned olivine chadacrysts and rounded grains of FeNi-metal and troilite. This texture resembles type I, FeO-poor chondrules. 3) A U-shaped plagioclase-nepheline-spinel intergrowth consists of an irregular mass of plagioclase completely altered to nepheline in the core region and enclosing many small, zoned hercynitic spinels. A similar assemblage occurs in Lancé inclusion 2LN [10]. The ophitic textures of both KB1 and KB2 show unambiguously that plagioclase is a primary phase and not metamorphic in origin. Manych PC1 is a 1 x 1.5 mm barred olivine chondrule consisting of olivine laths with interstitial low-Ca pyroxene and plagioclase (~An80). Some data for Manych PC1 were reported previously [1]; the data discussed below represent new analyses of plagioclase. Manych PC2 is a 3 x 4 mm metal-poor, poikilitic chondrule with large, unzoned orthopyroxene crystals enclosing formless, zoned olivine grains. FeO enrichment in olivine is visible as thin rims on ~Fa15 cores and along cracks. Plagioclase (~An77 - An85) occurs as laths and irregular crystals interstitial to olivine and pyroxene. Plagioclase in both PC1 and PC2 is free of alteration; the textural evidence for an igneous origin, however, is more equivocal than in the Kainsaz chondrules.

This study reveals isotopically normal Mg in all four chondrules. Olivine and pyroxene exhibit no evidence of intrinsic mass-dependent fractionation, $|F_{Mg}| < 4‰$/amu, and plagioclase contains no excess radiogenic $^{26}Mg^*$. From these data we calculate upper limits to the $^{26}Al/^{27}Al$ ratio at the time of crystallization of between 1.5×10^{-6} and 3.6×10^{-6} (Table 1). If the low abundance of ^{26}Al is due to the decay of ^{26}Al from a initial abundance, $^{26}Al/^{27}Al \sim 5 \times 10^{-5}$, the chondrules examined in this study formed 2.7 - 3.7 Ma after Type B CAI. This interval is fully consistent with the scenario inferred by [1] and leads to a nebular time scale consonant with the ~5 Ma difference in the relative ages of the oldest (CAI-rich) CV-chondrite, Vigarano, and the oldest chondrules in unequilibrated ordinary chondrites based on the ^{129}I-^{129}Xe system [11]. These new data reinforce the conclusion drawn by [1] -- ^{26}Al was much less abundant during the crystallization of POI and chondrules than during the formation of CAI. Only two of thirteen plagioclase-bearing objects examined over the course of this study and two of twelve POI [4] contain $^{26}Mg^*$. In at least five of the chondrules and all the POI the petrographic evidence clearly indicates plagioclase is a primary igneous phase and is not metamorphic in origin. Furthermore, in most chondrules and POI alteration of plagioclase is absent or very minor, suggesting disturbance of the Al-Mg system by solid-state exchange is unlikely. Alteration of plagioclase to grossular and/or feldspathoids is much more pronounced in CAI but no correlation between the extent of alteration and isotopic disturbance is evident [12, 13]. We conclude the striking difference in the ^{26}Al - ^{26}Mg record between CAI and chondrules cannot be attributed to secondary, post-crystallization processes but indicates most CAI formed prior to chondrules and that there was little overlap in their formation periods. The distinct difference in oxygen isotope compositions between CAI and chondrules is also consistent with this scenario [14]. Fine-grained chondrule precursors may have formed contemporaneously with CAI but nebular reprocessing continued for several Ma until ^{26}Al was no longer extant. The duration of the solar nebula inferred from these observations approaches 10 Ma, consistent with astronomical observations of circumstellar disks [8].

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Chondrule·	$^{26}Mg^*/^{27}Al$ (x10^6)	ΔT^1 (Ma)
Kainsaz KB1	< 3.6	2.7
Kainsaz KB2	< 2.6	3.1
Manych PC1	< 1.5	3.7
Manych PC2	< 1.6	3.5

[1] Time interval to obtain observed $^{26}Mg^*/^{27}Al$ from $(^{26}Al/^{27}Al)_0 = 5 \times 10^{-5}$.